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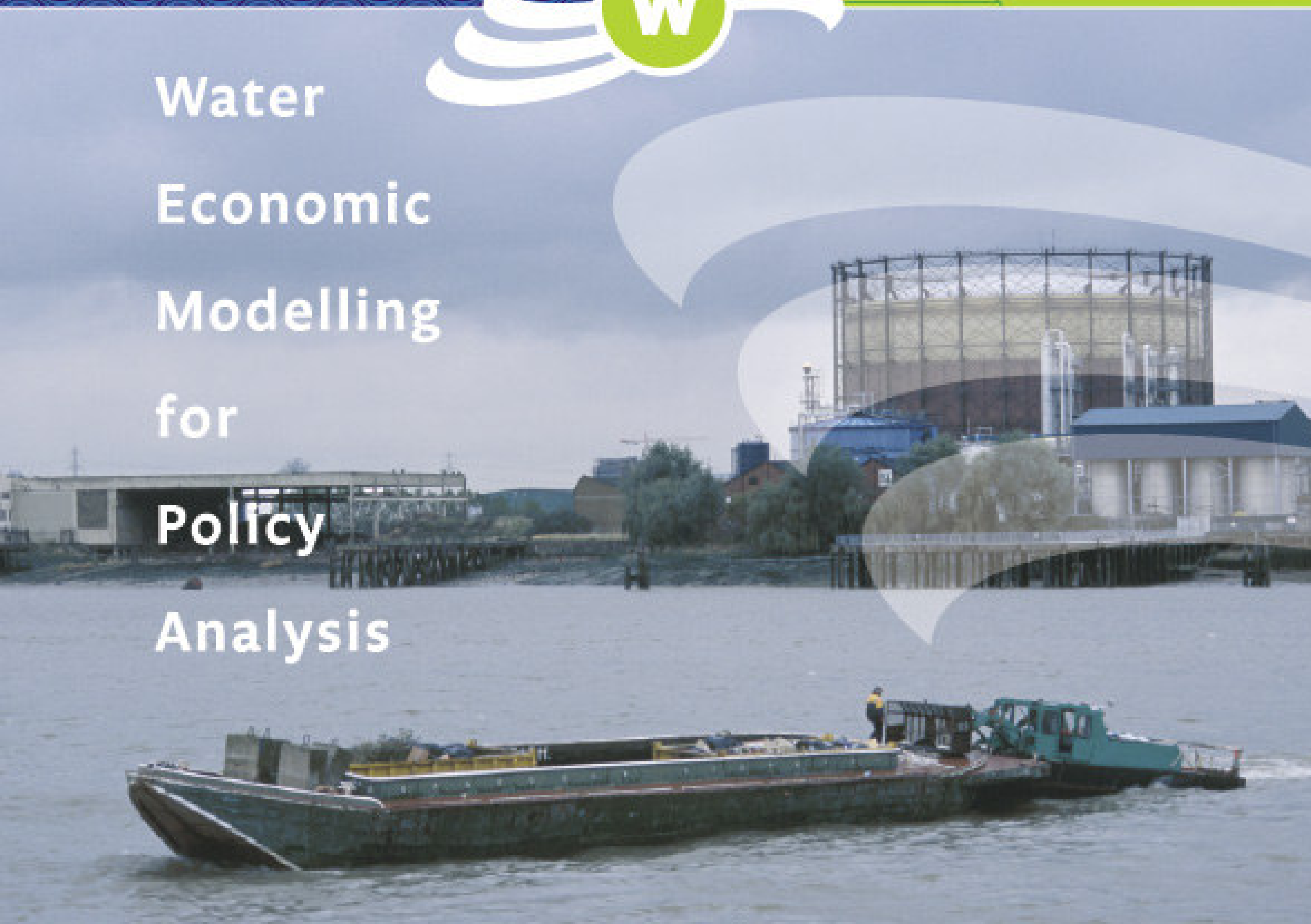

Assessing the cost-effectiveness of pollution abatement measures in agriculture, industry and the wastewater treatment sector

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Summary

One of the main challenges in the implementation of the European Water Framework Directive (WFD) is the selection of cost-effective programs of measures to reach the environmental objectives of good chemical and ecological status for all water bodies. According to the Economic Guidance document, the definition of the program of measures and the ranking of measures based on cost-effectiveness criteria is the key economic input into the preparation of the river basin management plans. The main steps in the cost-effectiveness analysis include the estimation of the costs of potential pollution abatement measures, the estimation of their environmental impacts and the subsequent ranking of cost-effective measures. The main objective of this report is to present the cost-effectiveness analysis carried out based on available data and information in the Netherlands for nutrient emissions to water from **agriculture**, heavy metal emissions to water from **industry** and nutrient emissions from the **wastewater treatment** sector. In the cost-effectiveness analysis the available data and information are filtered and validated in terms of their usefulness and robustness. Although surrounded by many uncertainties the results of the cost-effectiveness analysis are considered best educated guesses, providing important directions for the future prioritization of best available techniques within the economic sectors involved in the context of the WFD at national level.

1. Introduction

One of the main challenges in the implementation of the European Water Framework Directive (WFD) is the selection of cost-effective programs of measures to reach the environmental objectives of good chemical and ecological status of all water bodies. According to the WFD economic guidance (Wateco, 2002), the definition of the program of measures and the ranking of basic and supplementary measures based on cost-effectiveness criteria is the key economic input into the preparation of the river basin management plans. The main steps identified in the guidance include the estimation of the costs of each measure, the estimation of the environmental impact of each measure and the ranking of cost-effectiveness of measures. Hence, the necessary information basically relates to the costs of potential measures and their effectiveness.

Across European member states potential pollution abatement measures are currently identified and assessed in terms of their cost-effectiveness. Based on this work, gaps are identified in knowledge and information (see for instance Brouwer et al., 2007). In the Netherlands enormous efforts have been put into the collection of data about potential measures, their costs and effectiveness at national and regional level. Especially the assessment of the environmental impacts of potential measures is surrounded by a lot of uncertainty, but also the availability of cost data is limited. In many cases the evaluation of costs and effects is based on qualitative expert judgment.

Although lot of data and information have been collected a cost-effectiveness analysis was not yet carried out. In this report an attempt is made to analyze the available data and information about potential pollution abatement measures for the nutrients nitrogen (N) and phosphorous (P) and the heavy metal compounds arsenic (As), cadmium (Cd), copper (Cu), chromium (Cr), lead (Pb), mercury (Hg), nickel (Ni) and zinc (Zn) in agriculture, industry and the wastewater treatment sector in the Netherlands. Agriculture is the largest source of pollution for nutrients, followed by wastewater treatment plants (Figure 1.1). Wastewater treatment plants appear to be responsible for more than half of all the emissions of heavy metals to water, followed by traffic and transportation over land and water (labelled 'other' in Figure 1.2). In the case of commercial shipping, copper and zinc are the main pollutants, copper emissions originating from the use of antifouling paints and zinc emissions originating mainly from the use of zinc anodes to reduce corrosion of ships. Commercial shipping is not included and analyzed as a separate economic sector in this report due to the very low number of potential measures (limiting or prohibiting the use of antifouling paint and zinc anodes only) and the fact that a large part of the emissions of heavy metal compounds are caused by foreign vessels, the pollution of which is difficult to control by Dutch water managers.

The main objective of this report is to present and discuss the outcomes of the cost-effectiveness analysis carried out for the three sectors and to construct so-called cost-effectiveness curves. These curves show the relationship between the incremental costs of extra emission reduction based on the identified pollution abatement measures. In the cost-effectiveness analysis the available data and information are filtered and checked for their usefulness. The results of the cost-effectiveness analysis can be used in the context of the WFD to prioritize potential additional measures within the specific sectors.

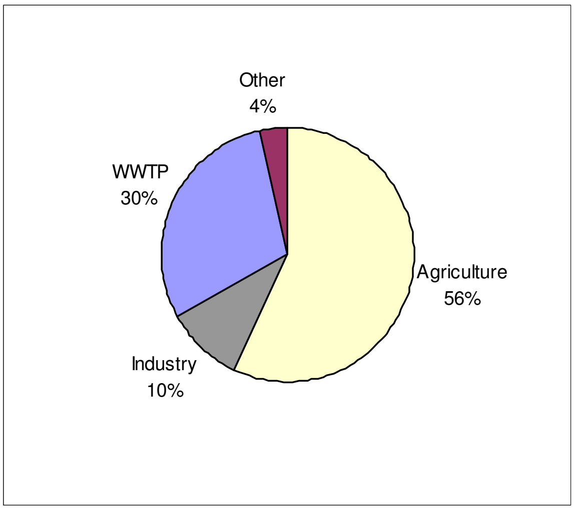

Figure 1.1 Contribution of sectors to the total emission of nutrients to water in 2001 (P-equivalents)

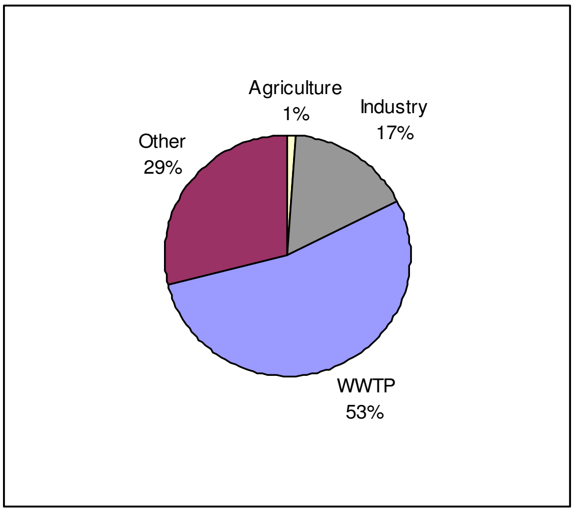

Figure 1.2 Contribution of sectors to the total emission of heavy metals to water in 2001 (1,4-DB Equivalents)

The structure of this report is as follows. Chapter 2 starts with a general description of the methodological issues related to cost-effectiveness analysis and the construction of cost-effectiveness curves. Chapter 3 to 5 present the results of the cost-effectiveness analysis for agriculture, industry and the wastewater treatment sector. These chapters are based on the more detailed WEMPA working papers (Soesbergen, 2007; Baan, 2007; Hellegers and Polman, 2007). Chapter 6 compares the approaches used for each sector and concludes.

2. Cost-effectiveness analysis[1]

2.1 General description

The purpose of a cost-effectiveness analysis (CEA) is to find out how predetermined targets, e.g. threshold values for nutrients or other pollutant loads in a river basin, can be achieved at least costs. Theoretically speaking, the least cost allocation of pollution abatement strategies is found if the marginal costs of the proposed measures are equal. The marginal costs of these abatement measures can for example be defined as the increase in total abatement costs when pollution loads are decreased by 1 ton or 1 kilogram per year. As long as marginal costs are not equal, it is theoretically possible to obtain the same level of pollution reduction at lower costs by shifting emission reduction from high cost measures to lower cost measures (Lise and Van der Veeren, 2002). In the WFD a CEA has to be carried out at river basin level. Hence, also the spatial distribution of costs plays an important role and the question where measures should be taken.

The various steps distinguished in a CEA are described below:

Step 1: Define the environmental objective involved

Step 2: Determine the extent to which the environmental objective is met

Step 3: Identify sources of pollution, pressures and impacts now and in the future over the appropriate time horizon

Step 4: Identify measures to bridge the gap between the reference (baseline) and target situation

Step 5: Assess the effectiveness of these measures in reaching the environmental objective

Step 6: Assess the costs of these measures

Step 7: Rank measures in terms of increasing unit costs

Step 8: Assess the least cost way to reach the environmental objective

These steps are taken in sequence, but important feedbacks may exist between steps. As information becomes available about the problem, the source-effect pathway and possible solutions, the same step may be revisited several times. The outline of the various steps shows that carrying out a CEA is a multi-disciplinary exercise, requiring the input of and collaboration between different scientific disciplines, such as natural scientists, economists and technical engineers, but also the input of policy and decision-makers as they determine the scope and objective of the analysis.

A number of approaches are used in practice at varying levels of complexity, scale, comprehensiveness and completeness for carrying out a CEA. These are discussed, for example, in Zhang and Folmer (1998). A distinction is made between bottom-up and top-down approaches. The bottom-up approach focuses on technological details of measures and their impact on individual enterprises (micro level), whereas top-down approaches usually consider the wider economic impacts of pollution abatement measures and

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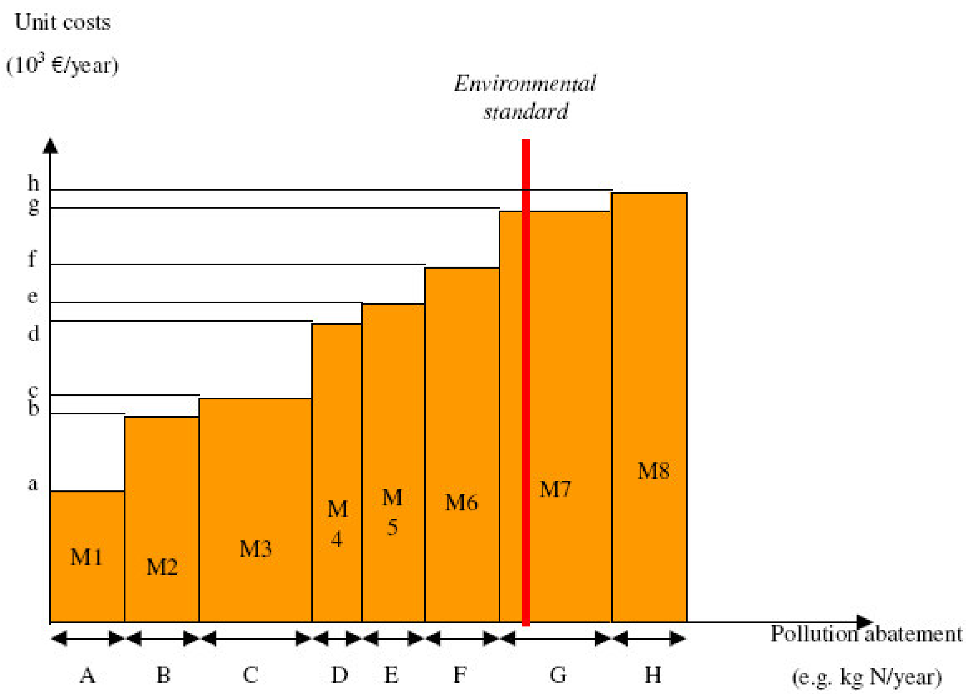
[1] Based on Brouwer et al. (2007).

strategies, often without detailed technical specification of the proposed measures (macro level). Bottom-up approaches can also be characterised as technical engineering approaches, often including detailed information about the technical characteristics of production processes and only limited information about the financial engineering costs of emission abatement technologies. Top-down approaches on the other hand focus more on the economic relationships and consequences involved and less on the technical specification of measures. Examples of bottom-up approaches include ad-hoc approaches comparing a limited number of abatement technologies usually on a very local scale based on their engineering costs and emission reduction capacity (see Figure 2.1) and the use of dynamic optimisation models where various abatement measures and technologies at enterprise or sector level are automatically prioritised with the help of linear programming (LP) techniques. Examples of top-down approaches are input-output and computable general equilibrium models. The inclusion of indirect effects depends on their relevance and the role they are expected to play in the decision-making procedure.

Figure 2.1: Illustration of a cost-effectiveness analysis

In its most simple form, the cost-effectiveness analysis can be depicted as in the figure below. Various possible measures (M1-M8) are ranked in increasing order of their unit costs. Besides a different unit cost (reflected by a-h on the vertical axis), each measure also has a specific pollution (nutrient or metal) abatement or reduction capacity (reflected by A-H on the horizontal axis).



The environmental objective (standard) is represented by the vertical red line. The least cost option to reach the environmental standard is found by implementing measures M1 to M6 and, if possible, part of measure M7. The total costs of implementing these measures is found taking the integral of the area M1-M8 from the origin until the environmental standard.

2.2 Specific methodological issues in the context of the WFD

Based on experiences in regional and international pilot river basins, (e.g. Boeters and Brouwer et al., 2006) the following key issues arise when trying to identify a cost-effective program of measures.

Identification of the environmental objective(s) involved

The concrete environmental WFD objectives for different types of water bodies (artificial, heavily modified, natural) are still unknown. Especially when aiming to develop an international river basin management, including transboundary programs of measures, some degree of common understanding and consensus is needed about the environmental objectives involved, and the measurement of progress in reaching these objectives through compatible monitoring programs.

Identification of the sources of pollution, pressures and impacts now and in the future over the appropriate time horizon

The exact relative contribution of different sources of pollution to the environmental water quality problem is often unknown, making it hard if not impossible to target different polluting sectors with specific measures to bridge the gap between the expected and desired state of the water body and river basin by 2015.

Quantification of the gap to be bridged

Related to the previous point, the gap to be bridged (problem definition) appears to be hard and in some cases even impossible to quantify given the lack of scientific knowledge and the uncertainties surrounding dose-effect relationships. In many cases a qualitative assessment of the problem at hand based on expert judgment is the best available estimation.

Identification of measures to bridge the gap between the reference (baseline) situation and target situation

The WFD distinguishes between basic and additional measures. Basic measures include measures, which help to achieve existing European water related legislation (e.g. Nitrates Directive or the Urban Wastewater Directive). Although the objectives of existing European and national policy are usually clear, it is less clear which types of measures have to be and will be implemented in the future in order to reach these objectives, not least because of the given uncertainties about their impact on water quality. Related to this is the implementation level of a particular measure in a specific sector and to what extent a measure can be implemented in addition to the existing or foreseen baseline technology. This requires an assessment of the degree of current and future implementation. In this report a baseline year is chosen (2000).

Another important issue is the distinction between technical measures and economic instruments. In practice, the distinction is often not clear, and measures and instruments are used interchangeably in the cost-effectiveness analysis. Evaluating technical measures and instruments simultaneously has the risk of double counting. Often, instruments and measures are implemented sequentially, not simultaneously, and there is therefore a real risk of double counting. In this report measures are defined as technical interventions, which result in a physical contribution towards the achievement of an objective (Van der

Figure 2.2: Example selection cost-effective program of measures to improve water quality in the West Scheldt estuary

An example of a cost-effectiveness analysis is presented in the table below (adapted from Baan, 1996). The table presents potential measures to improve water quality in the West Scheldt estuary, located in the south-east of the Netherlands (red area in the map), their effects and costs. A measure's cost-effectiveness is calculated by simply dividing the annual cost (column 3) by the annual effect (column 2). The measure with the lowest cost per unit pressure reduction is the most cost-effective measure. In this particular study, dredging is the most cost-effective solution, followed by the treatment of drinking water and the dislocation of the effluent from the wastewater treatment plant (WWTP) outside the estuary. Replacement of zinc plates on ships is the most costly measure per unit pressure reduction. The pressure reduction in the table below is expressed in 'Pressure Equivalents' (PE). This PE is based on the measures' emission reduction of different pollutants (N, P, Cd, Cu, Zn) in kg per year (estimated through expert judgment) compared to the threshold concentration levels of each pollutant in kg/m^3.

Measure	**Pressure reduction** (PE in 10^6 m^3/year)	**Cost** (10^6 €/year)	**Cost-effectiveness** (€/10^3 m^3 PE)
Sanitation industrial discharge	*1,435*	*2.0*	1.4
Agricultural runoff	7,057	17.3	2.5
Treatment drinking water	663	0.3	0.5
Coating roof gutter	200	0.8	4.0
Additional wastewater treatment WWTP	3,276	5.5	1.7
WWTP effluent dislocation outside estuary	4,681	2.5	0.5
Replacement zinc containing paint for ships	1,467	1.0	0.7
Replacement zinc plates ships	13	0.1	7.7
Dredging	11,000	3.4	0.3
Reduction polder drainage	45	0.1	2.2

Figure: Location study area

The table above is illustrative of a number of important methodological issues when selecting a cost-effective program of measures. First of all, the objective (water quality improvement) and the effects of different measures on water quality can be measured through a variety of different physical indicators or parameters. An important question is how to make these indicators comparable and compatible across measures targeted at different pollution sources and how to account for the fact that some measures may impact on different water quality parameters at the same time. In this specific case, the effects of measures on different pollutants were expressed in a common pressure equivalent using a specific conversion procedure based on equivalent weights. Second, measures can be taken at different points along the environmental source-effect chain. Preventing instead of treating water pollution may be another important decision criterion for the selection of measures. Examples here are dredging versus the dislocation of the WWTP effluent discharge point.

Third, given the spatial and temporal complexity of many water systems, pressure reduction in terms of the emission of kilograms of a pollutant per year is often more easily estimated and predicted than the actual impact of this pressure reduction on water quality in terms of milligrams of a pollutant per liter. Although it is water quality that is of prime interest in the selection and assessment procedure, pressure indicators are often used as proxies for the impacts on water quality given the uncertainties surrounding dose-response relationships and environmental damage functions.

Veeren, 2005). Examples of technical interventions include technological adjustments of wastewater treatment plants (e.g. use of other filtration techniques) or the removal of water sediments. Other examples are given in Figure 2.2.

Evaluation of the effectiveness of measures

The evaluation of the effectiveness of the proposed measures is probably the most troublesome in the entire decision process given the lack of knowledge and information and hence substantial uncertainties involved. Different indicators are used (e.g. chemical, biological), focusing on different points along the environmental dose-effect chain (e.g. pressure indicators and impact indicators), expressed in different units (e.g. kg/ha, mg/litre) making it hard to compare results from different types of measures in a compatible, meaningful way. Table 2.1 shows the approach taken in this report. Multi-criteria analysis (MCA) techniques may be another possible way of dealing with this plurality of measurement units in a systematic and coherent way. Significant differences also exist between the temporal and spatial scale at which measures are implemented in a basin and the associated differences in temporal and spatial impacts.

Table 2.1: Illustration of weighting procedures to make effects comparable

In this report, the nutrients nitrogen (N) and phosphorus (P) are aggregated into P-equivalents by dividing nitrogen values by 10, reflecting the lower environmental (eutrophication) impact of nitrogen. Heavy metal compounds are made comparable with the help of the freshwater Aquatic Eco-toxicity Potential index (fAETP) (Huijbregts et al.,2000). The advantage of this approach is that all substances are expressed in one single reference substance. For the fAETP the reference substance is 1,4-Dichlorobenzene. Weights are available for 181 substances. The fAETP values for the 8 heavy metals used in this report are shown in the table below.

fAETP weighing factors	
1.4-Dichlorobenzene	1
Mercury	1700
Cadmium	1500
Lead	9.6
Zinc	920
Copper	1200
Nickel	3200
Chromium	28
Arsenic	210

Freshwater Aquatic Eco-toxicity potentials for 8 heavy metals

Evaluation of the costs of measures

The distinction between different cost types (financial versus economic; fixed versus variable; direct versus indirect), cost items (e.g. one-time-off investment costs, annual management and maintenance costs, exploitation costs, overhead and depreciation costs) and their representation in time (e.g. annuity, (net) present value) is of utmost importance to arrive at a meaningful comparative analysis across measures and basins. It has to be made explicit which cost type and (proxy) estimation is being used, as there may exist significant differences between direct financial (engineering) costs and the usually broader defined direct and indirect economic costs. Different bottom-up and top-down calculation and estimation methods are available to assess the direct and indirect financial and economic costs of programs of measures (see the previous section). The way costs are estimated has important implications also for the assessment of disproportionate costs. In this report for the construction of sector specific cost-effectiveness curves costs of measures are calculated as the yearly total costs of technical measures in euros. These total costs consist of capital costs and operation costs. The capital costs consist of depreciation costs and interest costs of the investment[2]. The yearly capital costs are considered constant during the lifetime of the investment and converted into an annuity using an interest rate of 2.5 percent. The operation costs consist of labour costs, energy costs, overhead and other costs minus possible cost savings such as less consumption of raw material, sale of waste by-products etc.

Ranking of measures

Obviously, the ranking of measures in terms of increasing costs and based on this the selection of the least cost way to reach the environmental WFD objectives can only take place if the extent of the water quality problem (gap) is known and hence the necessary means (programs of measures) to solve the problem or bridge the gap, and the costs and effects of programs of measures are measured in comparable units. This requires inevitably the introduction of some degree of quantification in the analysis, including the qualification and quantification (in terms of orders of magnitude) of the main uncertainties involved (see Brouwer and De Blois, in press).

An important methodological issue regarding the ranking of measures is that they may not be completely independent or mutually exclusive. For example, one measure has to be implemented first before the other can be taken. These interacting measures may also affect the total environmental effect and a combination of measures may have a significantly different environmental effect than the environmental impact of the measures taken separately. The following situations and approaches have been suggested to deal with interactions (Van der Woerd et al., 2000):

i) Mutually exclusive measures can be dealt with by calculating the cost-effectiveness of these measures separately and then selecting the most cost-effective one of the two and include this most cost-effective measure in the CEA.

ii) Consecutive measures (measure B can only be implemented after measure A) can be dealt with by only including measure A or merging A+B into one new measure (and not including A and B separately). The decision to include A only or A+B together is partly dependent on the cost-effectiveness of measure B. If measure B is very cheap and very effective, not including it may result in a less cost-effective (sub-optimal) solution, while if measure B is very expensive and other measures are more effective

[2] Depreciation costs refer to a built-up part and an electro-technical part. In line with the report 'Costs and benefits in environmental policy; definitions and computational methods' (VROM, 1998) depreciation rates used in this report for the built-up part have a life time of 25 years, while depreciation rates for the electro-technical part of the investment have a life-time of 10 years.

in reducing emission levels, including it together with B is at the risk that none of the two will be selected even though measure A on its own can be very cost-effective.

iii) If the effect of a combination of two measures is smaller than the effect of the two measures separately, the total effect will be overestimated if both measures are included in the CEA independently. To solve this problem, a new measure can be introduced consisting of a combination of the two interacting measures and exclude the two separate measures. For example measure A reduces emission levels by 30% and measure B reduces the same emission level with 40%. Combined these measures should reduce emissions by 70%. However, if the effect of the combination of these measures is only 50%, then a new measure C (A+B) can be defined with an effect of 50% that excludes measures A and B. In the case of more combinations of measures, this approach can become very complex as too many combinations may become possible. This can then be solved by defining the effects in an incremental way. The effect of measure B will then be the difference between the effect of measures C and A (20%).

3. Cost-effective pollution abatement in agriculture

3.1 Introduction

Besides using groundwater and surface water for irrigation and drinking water for livestock, agriculture emits nutrients, pesticides and wastewater directly and indirectly into the water environment. As shown in the introduction, agriculture is the main source of pollution for nutrients in surface and groundwater bodies and therefore an important target group in the WFD. The Aquarein study (Van der Bolt et al., 2003) concludes that the consequences of the WFD are considerable for Dutch agriculture. According to this quick scan, two thirds of all agricultural land has to be taken out of production to reach the WFD objectives of good chemical and ecological status. The realisation of a relatively low WFD ambition level already requires a large number of measures. However, this study did not include the possibility of farmers adapting to the new WFD standards, i.e. how agricultural practices can be changed using new or alternative techniques. Moreover, market effects were not incorporated in the quick scan. Reducing production levels is expected to have an impact on agricultural markets and market prices and hence agricultural production systems.

This study focuses on measures to reduce the nitrogen surplus per hectare for the entire agricultural sector in the Netherlands. Measures to reduce phosphate are not considered because reaching an equilibrium between input and crop uptake of phosphorus is already part of the current Dutch manure policy. Figure 3.1 shows how nitrogen surplus in agriculture is estimated. Only part of this surplus is emitted to surface and ground water.

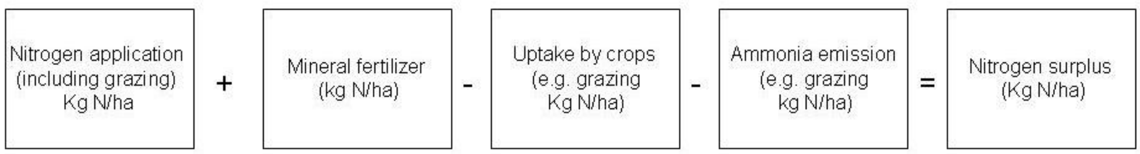


Figure 3.1 Calculation of nitrogen surplus in agriculture

The Dutch Regionalized Agricultural Model (DRAM) will be used to carry out the cost-effectiveness analysis (Helming, 2005).

3.2 Methodology

The DRAM is an agricultural activity based model, which offers the opportunity to calculate the costs of emission reductions due to changes in production structures and changes in land use. It is also able to compute market prices for land and manure quota, thus enabling the computation of second order effects of the WFD. The DRAM model simulates the behaviour of farmers and can therefore assess WFD measures that are implemented by farmers or those that affect farmers directly. For a more detailed description of the DRAM, see Helming (2005) and Hellegers and Polman (2007).

Possible measures that farmers can take and which are included in DRAM are:

- reduction of mineral fertilizer use
- reduction of animal manure application
- substitution between mineral fertilizer and animal manure
- export and large scale processing of animal manure
- adjustment of nutrient content in purchased feed concentrates
- structural regional adjustments in land use and number of animals.

With the help of the DRAM the pollution abatement costs are calculated of a 5, 10, 15, 20, 30, 35, 40, 45 and 50 percent reduction of the nitrogen surplus of 102.9 kg N/ha in the base situation in 2002. Based on studies by Grinsven et al. (2003), Helming (2005) and Statistics Netherlands it is estimated that 20 percent of the total nitrogen surplus is emitted to water (20.6 kg N/ha). In reality these emissions differ from year to year due to weather conditions and soil type. Weather conditions not only influence the growth of crops and emissions to groundwater and surface water, but also the possibilities for manure application. Autonomous changes, such as a decrease in the number of dairy cows due to an increase in the milk production per dairy cow, are not taken into consideration.

3.3 Results

Table 3.1 shows the cumulative abatement costs calculated with the DRAM model. Conform expectations, the marginal abatement costs increase when increasing amounts of emissions to water are reduced. The most cost-effective measures, i.e. the measures with the lowest cost per unit emission reduction, will be adopted first. Figure 3.2 shows the estimated cumulative abatement costs as a function of the emission level, starting on the right-hand side with an emission level of 20.6 kg N/ha. The cost-effectiveness curve is estimated using a functional form reflecting constant elasticity of substitution (CES). The abatement costs increase at an increasing rate at higher emission reduction levels.

Table 3.1 Agricultural emission reduction scenarios, costs and effectiveness calculated with DRAM (price level 2002)

Emission reduction scenario	Emission level (kg N/ha/yr)	MER (kg N/ha/yr)	MAC (€10^6/yr)	CER (kg N/ha/yr)	CAC (€10^6/yr)	CAC adjusted for current abatement costs (€10^6/yr)
5	19.55	1.03	4.26	1.03	4.26	93.03
10	18.52	1.03	19.95	2.06	24.21	112.98
15	17.49	1.03	47.08	3.09	71.29	160.06
20	16.46	1.03	71.05	4.12	142.79	231.56
30	14.41	1.03	189.07	6.17	331.86	420.63
35	13.38	1.03	133.32	7.20	465.18	553.95
40	12.35	1.03	256.54	8.23	721.72	810.49
45	11.32	1.03	338.93	9.26	1060.65	1149.42
50	10.29	1.03	639.87	10.29	1700.52	1789.29

Note: MER: Marginal Emission Reduction. CER: Cumulative Emission Reduction. MAC: Marginal Abatement Cost. CAC: Cumulative Abatement Costs.

The cumulative abatement costs increase to about 1790 million euro annually over and above current abatement costs when the emission levels of nitrogen to water in 2002 are reduced by 50 percent (i.e. 20 times the current abatement costs of about 88 million euro annually), while a reduction of 25 percent (a level of 15.4 kg N/ha) can be achieved at much lower costs, namely about 310 million euro per year, and a reduction of 40 percent (a level of 12.3 kg N/ha) for less than half of the total costs (about 800 million euro per year) of the 50 percent reduction scenario.

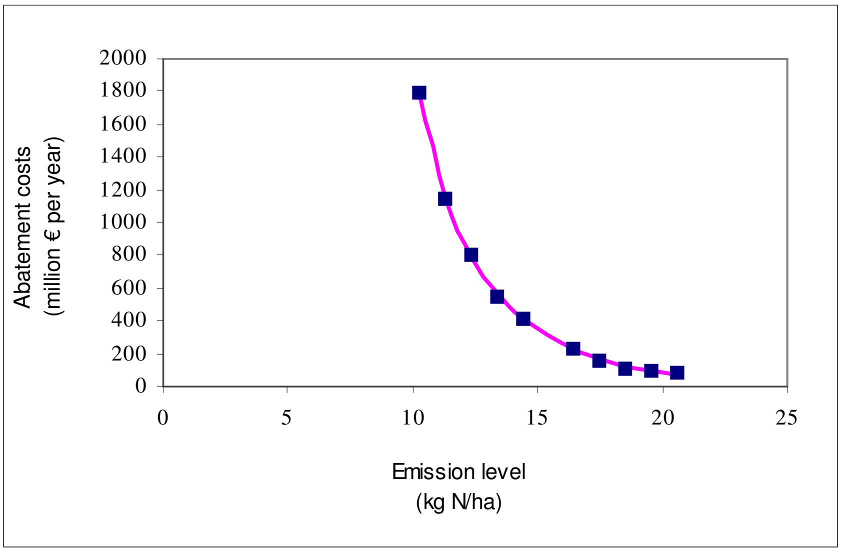


Figure 3.2 Pollution abatement costs as a function of reduced nitrogen emission levels in agriculture in the Netherlands

The cost-effectiveness curve shows that emission abatement costs for agriculture will become very high if emissions are reduced by more than 35% (emission level of 13.4 kg/N per ha). Costs increase rapidly below that standard, since the most cost-effective adjustments, i.e. those with the lowest costs per unit emission reduction, will have been taken first.

4. Cost-effective pollution abatement in industry

4.1 Introduction

Industry contributes roughly between 5 and 20 percent to the total load of heavy metals emitted to surface waters. For nutrients the contribution is less: 4 percent in the case of N and 5 percent in the case of P (Emissieregistratie 2007). The main sources of pollution of heavy metals are the chemical and metal industry. Nutrients originate mainly from the food processing and food products industry. A large part of the nutrient emissions, especially from smaller businesses, is treated in communal wastewater treatment plants (see chapter 5). For this reason the focus in this chapter will be primarily on the abatement of emissions of heavy metals from the chemical and metal industry. However, the pollution abatement measures discussed here may also be applicable to other industrial sectors and have an effect on the emission of nutrients and organic micro pollutants as well.

A distinction can be made between technical process-integrated measures and end-of-pipe measures. Process-integrated measures are usually implemented in new plants and production processes due to the high investment costs and lack of space. An important methodological issue when trying to estimate the cost-effectiveness of process-integrated measures with regards to their environmental impact is to distinguish between the efficiency gains due to technological change and the environmental cost related to the additional pollution abatement (De Boo, 1993; Pasurka, 2001). Both are an integral part of new technological measures and the environmental cost assessment depends to a large extent on the definition of the baseline technology.

The chemical industry and most other industrial sectors largely resort to end-of-pipe treatment techniques to reduce concentration levels of pollutants in wastewater. This chapter will focus on measures, which can be implemented in existing plants to further reduce emissions to water, and therefore only end-of-pipe treatment techniques will be discussed. The techniques considered in this chapter are Best Available Techniques (BAT) as described in the so-called BAT reference documents (BREF) produced in the context of the European Integrated Pollution and Prevention Control Directive (European IPPC Bureau, 2003). Only techniques that are capable of removing heavy metals and nutrients are considered. Figure 4.1 gives an overview of wastewater treatment techniques that can be applied in the chemical and metal industry.

The techniques in Figure 4.1 are already applied in industry to a certain extent. The different techniques are in most cases not stand-alone techniques but rather part of combinations of techniques. Especially the tertiary treatment techniques need pre-treatment to prevent clogging, fouling and damaging of the installations. Possible combinations and interactions are also shown in Figure 4.1. In some cases, wastewater is returned to a pre-treatment technique. The residue from wastewater treatment ends up as sludge in most cases that has to be disposed of separately by incineration or dumping. New techniques are more aimed at recycling removed materials. For a more detailed description of the possible techniques, see van Soesbergen (2007).

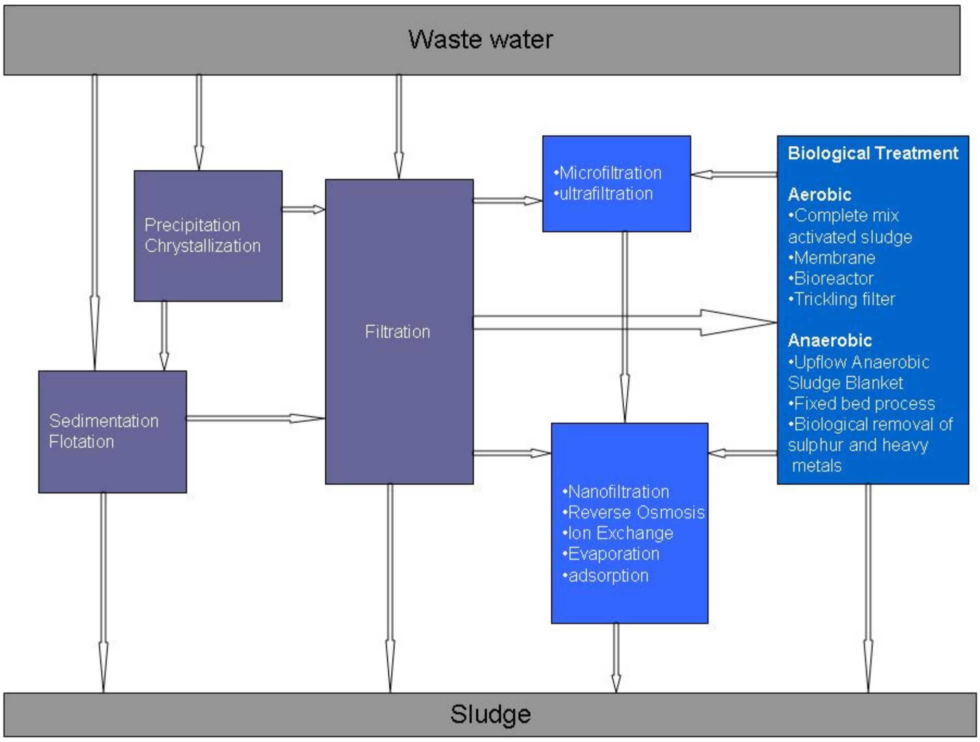


Figure 4.1 Possible wastewater treatment techniques in industry

4.2 Methodology

An important issue when trying to compare different pollution abatement measures in industry based on their cost-effectiveness is the scale of implementation. Different measures may be more or less cost-effective in industry depending on the size of the company where the measure has to be implemented and the existing baseline technology. In order to be able to compare the cost-effectiveness of additional pollution abatement measures in the chemical and metal industry, a representative firm is created based on the average wastewater flow in larger companies, i.e. companies with more than 100 employees. About 90 percent of all emissions of heavy metals originate from companies with more than 100 employees. These companies are furthermore all part of a voluntary agreement and have to report under the Environmental Reporting Act (FO-industry, 2003). Table 4.1 lists the number of companies in the chemical and metal industry with more than 100 employees and the applied average flow rates for the analysis.

Table 4.1 Reference companies used in cost-effectiveness analysis for industry

Sector	Number of companies	Average flow rate (m^3/day)
Chemical industry	135	5,000
Metal industry	165	1,000

Sources: Statistics Netherlands and FO-industry (2003).

This approach limits the number of companies within industry to the main sources of pollution capable of implementing additional end-of-pipe pollution abatement techniques. Implementation levels of the measures play an important role in the cost-effectiveness analysis too. However, information about current implementation levels is scarce. Considerable effort was put into the evaluation of the restricted access (confidential) environmental cost data base collected on an annual basis by Statistics Netherlands for the publication "Kerncijfers milieukosten van bedrijven" to find out how many companies in the chemical and metal industry report about the implementation of specific wastewater treatment technologies in different years. Statistics Netherlands conducts a survey every year in industry (10 employees and more) to collect data about investment and exploitation costs for environmental protection activities. The authors were given access to the data base, but the information in the database appeared to be of very limited use, most importantly due to insufficient technical detail about the specific measures taken, but also lack of information about the effect of the measures, including the specific pollutants removed and the emission reduction potential of measures. The implementation level is therefore fixed here at 10% for all measures in the base year 2005. Data and information about the costs and environmental effects of possible pollution abatement measures are based on available international data sources (European IPPC Bureau, 2003) and national data (DHV, 2003; RIZA, 2004; van der Burg, 2006).

Annual costs are based on investment and running costs converted into annuities at an interest rate of 2.5 percent and a technical lifetime of the different measures as described in chapter 2. The capacity of a wastewater treatment technique influences the investment costs due to the existence of economies of scale in implementation. The investment costs decrease when the capacity is extended as follows (RIZA, 2004):

$$(I_2/I_1=(C_2/C_1)^n \qquad (1)$$

where I is the investment cost, C is the wastewater treatment capacity (wastewater flow) and n is a scaling factor with a value between 0.4 and 0.95 depending on the type of technique. Operation or running costs are assumed to be a linear function of the investment costs.

In order to be able to compare the pollutant removal efficiency of the different techniques, the weighting procedure outlined in chapter 2 is used. Concentration levels of polluting substances in the base year 2005 and the removal efficiency of additional measures are converted into fAETP-equivalents. The effectiveness of different measures is estimated in terms of the percentage reduction of emission levels in the base year 2005. This is done for the chemical and metal industry separately to produce two distinct cost-effectiveness indicators, one for each industry.

So, the various steps to calculate the cost-effectiveness of different pollution abatement measures in the chemical and metal industry include:

- estimation of the investment and operational costs for each pollution abatement measure for the reference wastewater flow (representative company) and conversion of these two types of costs into an annuity;
- estimation of the annual pollutant reduction capacity of each measure as a percentage of the 2005 fAETP emission level of the reference wastewater flow (representative company);

- ranking of possible pollution abatement measures based on their cost-effectiveness (€ per unit reduced fAETP), taking into account that some measures are mutually exclusive while others are taken consecutively.

Based on the calculated cost-effectiveness of possible measures a cost-effectiveness curve can be drawn for the chemical and metal industry, from which the direct costs of pollution abatement can be calculated for the entire sector.

4.3 Results

The results of the cost-effectiveness analysis are presented in Table 4.2. The annual costs of the measures are the same in each industry (the same baseline technology implementation level is assumed due to lack of more detailed information), but not the load reduction capacities of measures in both industries due to different baseline emission levels. Cost and effectiveness are calculated for a representative company in the chemical and metal industry based on a reference wastewater flow of 5000 and 1000 m^3/day respectively. The measures in Table 4.2 are already ranked according to their cost-effectiveness for the chemical sector. Although the unit costs are substantially higher in the chemical industry than in the metal industry (on average an order of magnitude of 3 times higher), the ranking of measures in the two sectors is more or less the same except for some minor differences.

In both the chemical and metal industry microfiltration is the most cost-effective measure, followed by precipitation and flotation techniques. Microfiltration is like ultrafiltration a membrane process, which segregates liquids that permeate through a membrane into a retained concentrate. The unit cost of microfiltration is around 42 euro per unit removed dichlorobenzene equivalent in the chemical industry and 64 euro in the metal industry. The difference is mainly due to differences in the reference flow. In the chemical industry the wastewater reference flow is five times higher than in the metal industry. The unit costs per flow level are the same in both industries (€0.04/m^3).

Precipitation is the second most cost-effective measure in combination with coagulation or flocculation, costing around 70 euro per unit removed dichlorobenzene equivalent in the chemical industry and 17 euro per unit removed dichlorobenzene equivalent in the metal industry (€0.05/m^3 in both industries). Precipitation is a process of precipitating particles with chemicals if particles are too small to be separated by gravitational force so they can be separated by an additional process, such as sedimentation, filtration or air flotation.

Flotation is a process whereby solid or liquid particles are separated from wastewater through air bubbles. The buoyant particles accumulate at the water surface and are collected with skimmers. Dissolved Air Flotation (DAF) is a method where air is injected into the flotation unit whilst the liquid is under pressure and followed by a release of pressure. Induced Air Flotation (IAF) is a method where fine bubbles are drawn into the wastewater through an induction device like a venture or orifice plate. DAF in combination with activated sludge is slightly more cost-effective than DAF only in the chemical industry compared to the metal industry.

Figure 4.2 shows the cumulative abatement cost curve for the removal of heavy metals in the chemical industry as a whole based on emission levels for the year 2005 using a CES function. The cost-effectiveness curve in Figure 4.2 includes combinations of measures presented in Table 4.2 and is therefore not directly comparable with the values presented in Table 4.2.The emission reduction starts at the right-hand side from the base year 2005. The abatement costs increase quickly and exponentially when moving to the left. The maximum load removal is 158 million fAETP equivalents, which equals 81 percent of the total emission level of heavy metals from the chemical industry in the year 2005. The total costs at this removal level can be as high as 450 million euro per year assuming a wastewater reference flow of 5000 m^3/day. Reducing 70 million fAETP equivalents or 35 percent of the emission level in 2005 comes at a 8 times lower total cost (about 55 million euro per year).

Table 4.2 Cost-effectiveness of potential additional wastewater treatment techniques in the chemical and metal industry (price level 2005)

	Annual cost (€10^3)		**Annual load reduction** (10^3 1.4-DB equivalent)		**Cost-effectiveness** (€/10^3 1.4-DB equivalent)	
Wastewater treatment technique	*Chemical*	*Metal*	*Chemical*	*Metal*	*Chemical*	*Metal*
Microfiltration	52	14	1,238	222	42	64
Precipitation (coagulation/flocculation)	70	17	1,173	210	60	82
Dissolved Air Flotation (DAF)/Refinery	77	18	1,173	210	66	88
Induced Air Flotation (IAF)/Refinery	82	20	1,173	210	70	94
DAF/activated sludge	121	27	1,173	210	103	130
DAF	123	26	1,173	210	105	123
Filtration	116	24	912	163	127	148
Evaporation	219	48	1,173	210	187	229
Ultrafiltration	296	68	1,173	210	253	322
Absorption with activated carbon	267	55	1,043	187	256	293
Nanofiltration	483	110	1,173	210	412	525
Complete mix activated sludge	591	149	1,043	187	567	801
Membrane bioreactor	734	150	1,238	222	593	677
Ion exchange	902	184	1,043	187	865	984
Reverse Osmosis	3,200	847	1,238	222	2,585	3,819
Sedimentation (laminar or tube settler)	2,648	533	912	163	2,902	3,260

In order to evaluate the robustness of the calculated cost-effectiveness indicators, the analysis was also carried out assuming different average wastewater flow rates and implementation levels of the measures involved. Both have a significant impact on the costs of additional pollutant removal in the chemical industry. For example, the total costs of eliminating 81 percent of the emission load of heavy metals almost double when assuming a twice as high wastewater reference flow of 10,000 m^3/day. Furthermore, if initial implementation of all measures in the baseyear 2005 is fixed at 25% instead of

10% the maximum total costs reach 350 million euro but at this cost only 68% of the total emission level of heavy metals from the chemical industry can be removed.

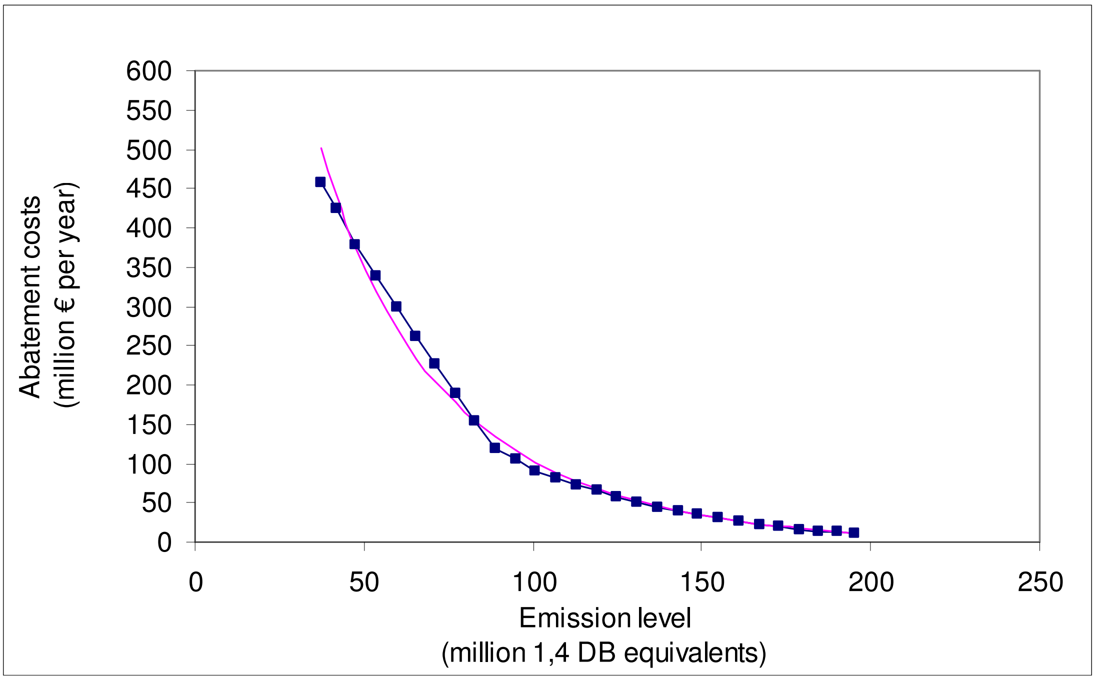


Figure 4.2 Pollution abatement costs as a function of reduced emission levels of heavy metals in the chemical industry in the Netherlands

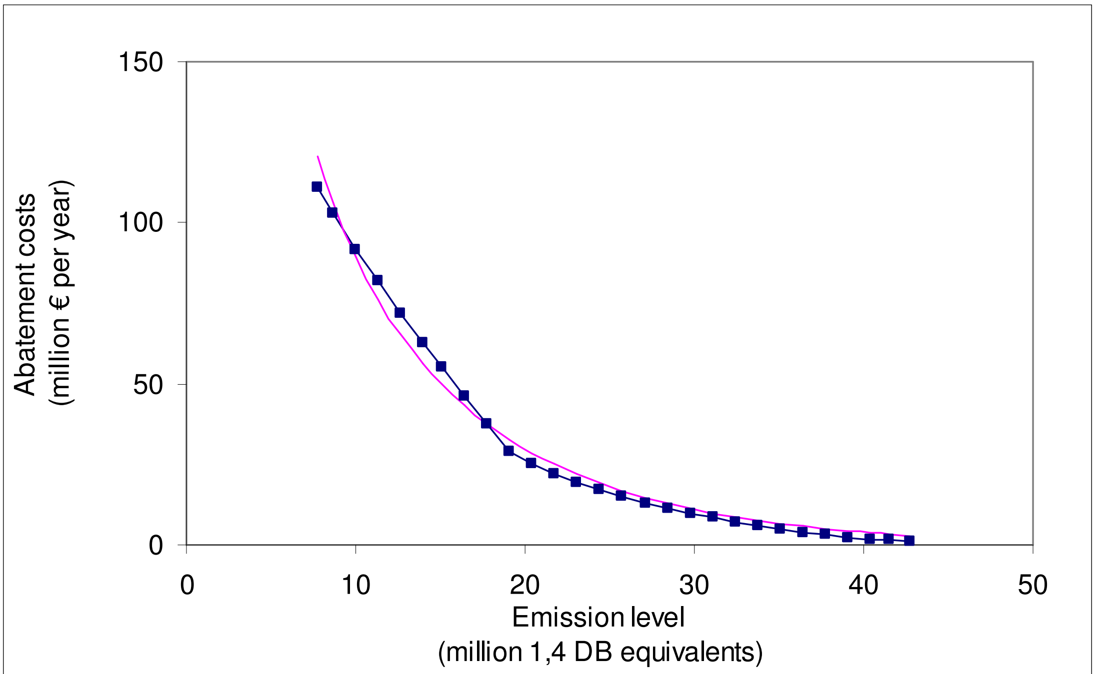


Figure 4.3 Pollution abatement costs as a function of reduced emission levels of heavy metals in the metal industry in the Netherlands

Figure 4.3 shows the cost-effectiveness curve for the removal of heavy metals in the metal industry as a whole based on emission levels for the year 2005 and again using a

CES transformation of the raw data. The maximum removal of heavy metals in industrial wastewater is in this case 35 million fAETP equivalents, which is equal to 80 percent of the total emission of heavy metals in the metal industry in the year 2005. The total costs of the maximum load reduction in the metal industry are about 110 million euro per year assuming that the average wastewater flow level is 1000 m^3/day. Reducing the heavy metal content of wastewater in the metal industry by 35 percent instead of almost 80 percent comes at a cost, which is 8 times lower (about 13 million euro per year). Also here different assumptions regarding the wastewater flow levels and implementation level of measures result in substantially different cost estimations of additional pollution load reduction. Assuming for instance a reference flow level of 2500 m^3/day the total costs increase more or less proportionally with a factor 2.5 compared to an average flow level of 1000 m^3/day at the level of maximum reduction potential. If the initial implementation level of all measures is fixed at 25%, the maximum total cost reach 96 million but the maximum reduction at that cost will only be 29 million fAETP equivalents.

5. Cost-effective pollution abatement in communal wastewater treatment plants

5.1 Introduction

This chapter addresses the estimation of the costs and effectiveness of measures to reduce waste loads entering surface waters from communal wastewater treatment plants (CWTP). Several sources contribute to the waste loads entering sewer systems along different pathways (see Figure 5.1). The concentration level of substances in wastewater discharges depends on the specific source and pathway.

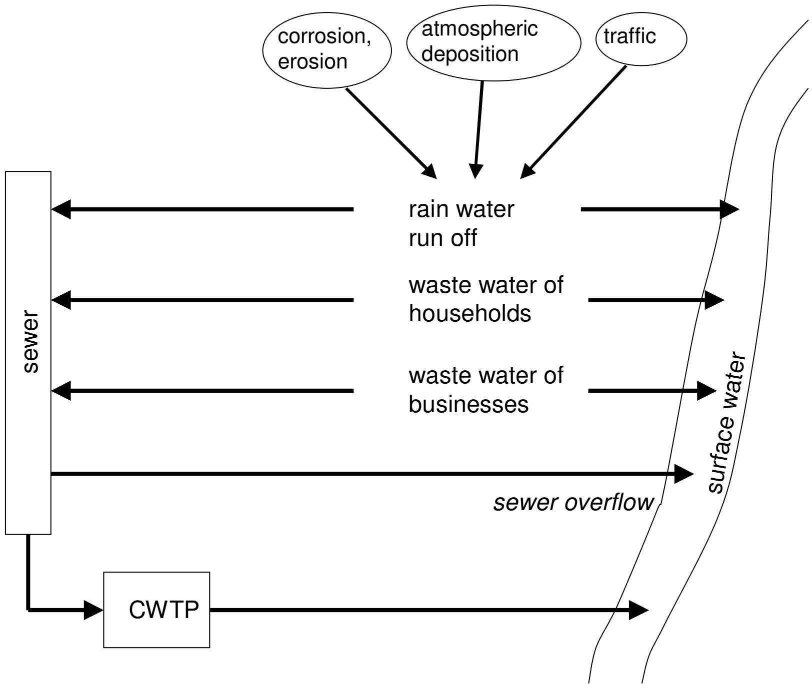


Figure 5.1 Sources of waste loads entering sewer systems polluting surface water

In the case of water pollution by sewer systems, three pollution abatement approaches are possible:

1. measures aimed at decreasing the waste loads entering the sewer system at the source, for example reducing wastewater discharge from households and businesses, reducing corrosion and erosion of sink roof gutters;
2. measures aimed at reducing untreated discharges from the sewer system like storm water overflow;
3. measures aimed at reducing concentration levels in CWTP effluent by upgrading the treatment process and reducing waste loads.

The measures considered in this study focus on the latter approach of upgrading the treatment capacity of CWTP, using the overall baseline technology in CWTP in 2005 as a starting point. The possibilities of abating emissions at the source like reducing roof gutter erosion are considered very limited. Current policy to reduce storm water overflow is already effective: the waste loads entering surface water from overflows are relatively small. Moreover, it turns out that abating sewer overflows is not a very cost-effective measure compared to additional wastewater treatment in CWTP (Hulskotte et al., 2007).

5.2 Methodology

Additional treatment techniques are aimed at the removal of one or more substances like N and P, heavy metals and organic micro pollutants. The removal efficiency for each substance depends on the mix and concentration of pollutants present in the water influx and process control. Possible techniques that can be applied to increase the removal of nutrients include (Vermeulen, 2003; de Jong et al., 2005):

1. Extension of active sludge process. With this technique the concentrations of N and P in the effluent can be reduced to 10 and 1 mg/l respectively. Since heavy metals and organic micro-pollutants are absorbed in the sludge, these substances are also removed.
2. Adding methanol to the wastewater as a carbon source to degrade nitrate. This technique can reduce the concentration of N in the effluent from 10 to 2.2 mg/l.
3. Adding an iron compound (or another chemical) as a flocculation agent and filtration of the wastewater. With this technique the concentration of P can be reduced from 1 to 0.15 mg/l. Heavy metals are absorbed in the iron-sludge by-product and are also removed from the wastewater.

The best available technique to remove suspended solids (sludge) is sand filtration (Janssen et al., 2006). The removal efficiency of nutrients of these additional techniques depends on the quantity of additional chemicals, the rate of filtration, and the composition of the filter bed. How much heavy metals are removed depends on the influent concentration and the process conditions, and is not well known.

Based on the above mentioned techniques, two additional treatment measures are (de Jong et al., 2005 and Wiegant et al., 2006):

- One step flocculation, capable of removing about 50 percent of N and P in the wastewater.
- Two step flocculation, capable of removing about 80 percent of N and 85 percent of P in the wastewater (concentrations of 2.2 mg/N/l and 0.15 mg P/l)

Cost estimates for these additional treatment measures for design capacities of 20,000 and 100,000 population equivalents (PE) are presented in Table 5.1. The design capacities are furthermore based on 1.5 times the dry weather inflow. With this design capacity 85 percent of the total inflow of wastewater can be treated. The cost estimates are based on the assumption that the effluent already meets the Urban Waste Water Directive (UWD) standards, which came into force in 1995 and 1996 for P and N respectively.

Table 5.1 Investment costs in million euros of additional wastewater treatment in CWTP (price level 2005)

	Design capacity	
Type of treatment	**20,000 PE**	**100,000 PE**
Removal of N en P with one step flocculation	€2.2 million	€3.6 million
Removal of N and P with two step flocculation	€3.2 million	€5.4 million

Source: De Jong et al. (2005) and Wiegant et al. (2006)

Although these techniques have the ability of removing heavy metals and organic micro pollutants too, additional wastewater treatment in CWTP is mainly targeted at the abatement of nutrients.

To compare removal efficiencies for the different techniques the weighting procedure as outlined in chapter 2 is used. Annual costs are based on annuities with an interest rate of 2.5 percent and a technical lifetime of fixed capital as described in chapter 2. Based on the cost data provided by De Jong et al., (2005) and Wiegant et al., (2006) it is estimated that about 40 percent of the investment costs are related to civil works and 60 percent to electro-mechanical constructions. Annual maintenance costs are estimated at 0.5 percent of the investment costs for civil works and 3 percent for electro-mechanical constructions, yielding an average of 2 percent for the total annual maintenance costs.

To calculate the cost-effectiveness of additional removal of N and P in CWTP the following steps are distinguished. First, the investment costs presented in Table 5.1 are converted into annual costs for the additional removal of N and P for different CWTP capacity classes. Second, the removal of N and P in the waste loads are estimated based on the fact that the total flow of treated wastewater in CWTP is 1,8 billion m^3 per year (RIONED, 2005) and the assumption that this flow is proportionally related to the design capacity and influent concentration levels are conform the UWD standards. The estimated load reductions are converted into P-equivalents. Finally, the cost effectiveness of different combinations of capacity design classes and technique are calculated in terms of euros per kg P-equivalent, resulting in a ranking of possible combinations. Total costs are estimated through upscaling and aggregation of the cost and effectiveness of measures faced by a representative CWTP over the 385 CWTP in the Netherlands classified according to different design capacities.

5.3 Results

The results of the cost-effectiveness analysis are presented in Table 5.2. The combinations of techniques and design capacities are ranked according to their cost-effectiveness. The estimated cost-effectiveness varies from 32 euro for the most cost-effective combination (two step flocculation in a CWTP with a design capacity of more than 150 thousand PE) to 134 euro per kg P-equivalent (two step flocculation in a CWTP with a design capacity of less than 20 thousand PE). Based on the data in Table 5.2 the cost-effectiveness curve in Figure 5.2 can be drawn using a CES function for the wastewater treatment sector as a whole.

Table 5.2 Ranking of combinations of wastewater treatment techniques and design capacities based on their cost-effectiveness (price level 2005)

Technique	**Design capacity** (1,000 PE/yr)	**Annual costs** (€10^6)	**P-equivalents removed** (10^6 kg/yr)	**Cost-effectiveness** (€/kg P-equivalent/yr)
two step flocculation	>150	43.3	1.35	32
one step flocculation	20 – 100	57.3	1.35	43
two step flocculation	100 – 150	23.0	0.44	52
two step flocculation	20 – 100	20.5	0.26	78
one step flocculation	<20	23.2	0.22	107
two step flocculation	<20	8.8	0.07	134

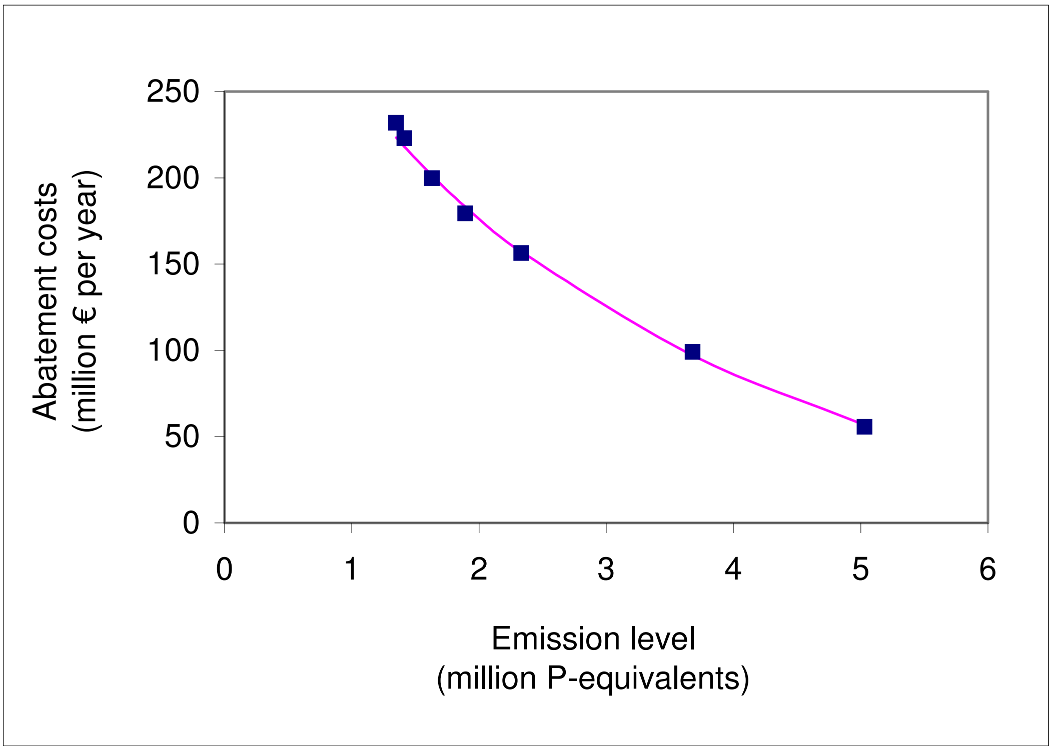


Figure 5.2 Pollution abatement costs as a function of nutrient reduction levels in communal wastewater treatment plants in the Netherlands

As can be seen from Figure 5.2, the total annual costs can be as high as 176 million euro per year to remove 3.38 million kg P-equivalents. N and P concentration levels can be removed further by further increasing the wastewater treatment capacity of the CWTP. If the design capacity is doubled to three times the dry weather inflow instead of the 1.5 assumed here, nearly the entire influx of wastewater can be treated, but the costs increase in that case by 40-70 percent for a relatively small additional abatement of N and P (de Jong et al., 2005, Wiegant et al., 2006). Further removal of N and P is also possible by adding extra chemicals during the wastewater treatment process, making the treatment more expensive. The cost-effectiveness of the use of additional chemicals in the treatment process could not be determined here.

6. Conclusions

The main objective of this report is to present and discuss the cost-effectiveness analysis that was carried out based on available data and information in the Netherlands for nutrient emissions to water from agriculture, heavy metal emissions to water from industry and nutrient emissions from the wastewater treatment sector. In the case of industrial wastewater also information from the international IPPC BAT reference documents was used. The measures introduced here are general in nature. Cost and effectiveness data for water pollution abatement measures at national and regional level are limited. Qualitative expert judgments are often required to assess the cost-effectiveness of WFD measures. Both the cost and effect assessments are surrounded by lots of uncertainties. The costs of pollution abatement measures and their environmental impacts quantified in this report – based on existing literature and models – are nevertheless considered best educated guesses, providing important directions for the future prioritization of best available cost-effective techniques within the economic sectors involved in the context of the WFD at a national level.

At regional level the specific context and reference situation, including the nature and implementation degree of the baseline technology, plays an important role and determines the additional implementation possibilities of specific measures. Although not investigated here, the costs and environmental impacts of the same measure are expected to differ substantially between regions when faced with significantly different baseline situations. The values presented in this report are not directly transferable to a specific regional context and should therefore be used very cautiously in a regional context. In the generic assessments presented here, the level of implementation and basic assumptions about wastewater flow levels, treatment capacity and combinations of measures in industry and the communal wastewater treatment sector appear to be important determinants of the cost and effects of technical abatement measures. These reference conditions usually differ per region.

Another important issue is that the reference years differ for agriculture (2002) and industry and the wastewater treatment sector (2005). Since 2002 a number of additional measures have been taken to reduce emission levels to meet existing environmental standards in European and national legislation. Hence the baseline technology and emission levels have changed since 2002 and this has to be accounted for in the application of the cost-effectiveness results presented in this report. Although considerable effort was put into the identification of the baseline technology, especially in industry using the environmental cost database from Statistics Netherlands, assumptions had to be made about the implementation degree of the measures considered in this report.

Important methodological issues in this report include the fact that even though a cost-effectiveness analysis starts with the identification of the objective to be reached, the specific environmental objectives in the WFD are still unknown, and hence the gap to be bridged with the identified pollution abatement measures. Instead, the cost-effectiveness analysis carried out for the three sectors simply assesses the emission reduction capacity of a number of technical measures or combinations of measures without detailing the target level. In agriculture the maximum reduction of nitrogen emissions to water is fixed at 50 percent of emission levels in the year 2002, while the pollution abatement measures in the wastewater treatment sector and industry are expected to be able to reduce emission levels in 2005 with maximum about 70-80 percent. Ideally, these emission reductions are subsequently linked to their impact on water quality and the desired water quality level of good chemical and ecological status based on concrete chemical and/or biological threshold values or standards. Although a more thorough examination of the ranking of the identified cost-effective measures taken at the source of pollution should take place, the ranking of the measures within the same sector is expected to stay more or less the same when also including their effect on water quality.

The total direct costs for the specific sector estimated based on these maximum emission reduction levels are highest for agriculture (about 1790 million euro per year), followed by the chemical industry (about 450 million euro per year), the wastewater treatment sector (about 180 million euro) and the metal industry (about 110 million euro per year). A logical next step would be to compare and prioritize potential measures across sectors. However, this requires that the cost-effectiveness indicators are measured in comparable units, which is currently not the case. The reduction of nitrogen from agriculture can be recalculated relatively easy into a P-equivalent per year, making a comparison between communal wastewater treatment and agriculture possible. Important remains in this case that also the relative contribution of a sector to the water quality problem is taken into consideration.

Finally, although the importance of linking emissions to water quality was already stressed, it is important to point out that the cost-effectiveness analysis for the three sectors presented here only refers to chemical substances, not ecological water quality. Furthermore, the cost estimations are direct financial costs, and do not include the wider macro-economic costs due to possible indirect effects on the economy as a whole, or the economic benefits of reaching a good chemical or ecological status for all water bodies in the Netherlands. In the case of agriculture the DRAM estimations are able to also account for the wider economic effects of the existing manure market. The total direct and indirect economic costs of national emission reduction scenarios and their impact on water quality are addressed in Dellink and Linderhof (2007) and Brouwer et al. (in press), using a (top-down) applied general equilibrium model. In this report, a bottom-up approach was used for all three sectors to assess the cost-effectiveness of pollution abatement measures. For agriculture this was done based on a linear programming model, for industry and the communal wastewater treatment sector a so-called 'ad hoc' approach was used (see chapter 2.1), where individual measures were simply ranked based on their estimated cost and effectiveness.

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WEMPA report

Reportnumber	*Authors*	*Title*
WEMPA Report-01	Roy Brouwer	Toekomstige beleidsvragen en hun implicaties voor de ontwikkeling van een integraal water-en-economie model
WEMPA Report-02	Paul Baan Aline te Linde	Inventory of water system models
WEMPA Report-03	Stijn Reinhard Vincent Linderhof	Inventory of economic models
WEMPA Report-04	Rob van der Veeren	Development of policy scenarios and measures

WEMPA report

Working paper	*Athors*	*Title*
WEMPA working paper-01	Paul Baan	Households and recreation: use and value of water
WEMPA working paper-02	Paul Baan	Emissiereductie RWZI's en Huishoudens
WEMPA working paper-03	Sjoerd Schenau	Data availability for the WEMPA project
WEMPA working paper-04	Rob Dellink Vincent Linderhof	Dynamic AGE model for water economics in the Netherlands (DEAN-WEMPA): first results
WEMPA working paper-05	Rob Dellink Vincent Linderhof	Dynamic AGE model for water economics in the Netherlands (DEAN-WEMPA): an update
WEMPA working paper-06	Frans Oosterhuis	Ervaringen met verhandelbare rechten in het waterkwaliteitsbeleid van de Verenigde Staten
WEMPA working paper-07	Frans Oosterhuis	Opportunities for the use of tradeable permits in Dutch water quality policy
WEMPA working paper-08	Paul Baan	Assessing the cost-effectiveness of pollution abatement measures in communal wastewater treatment plants
WEMPA working paper-09	Petra Hellegers Nico Polman	Assessing the cost-effectiveness of pollution abatement measures in agriculture
WEMPA working paper-10	Arnout van Soesbergen	Assessing the cost-effectiveness of pollution abatement measures in industry

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